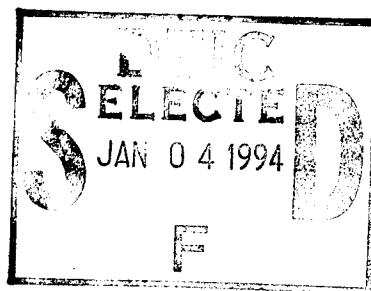


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Environmental Research Papers, No. 1153

A BRIEF HISTORY OF LASER GUIDED LIGHTNING DISCHARGE MODELS AND EXPERIMENTS

Matthew A. Kozma



5 July 1994

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Illustration

1. Electrical Discharge in Laboratory Cell ($1/7$ atmosphere) Induced by a Nanosecond Pulse 6

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Acronyms And Abbreviations

AFB	Air Force Base
C	Coulomb
CG	Cloud-to-ground Lightning
CENG	Centre Etudes Nucleaires de Grenoble
GPAA	Atmospheric Structure Branch, Atmospheric Sciences Division, Geophysics Directorate, Phillips Laboratory (PL)
GW	Giga-watt (10^9 watts)
IC	Intra-cloud Lightning
J	Joule
KrF	Krypton-fluoride
LGLD	Laser Guided Lightning Discharge
NASA	National Aeronautics and Space Administration
nm	nano-meter (10^{-9} meters)
ns	nano-second (10^{-9} seconds)
PL	Phillips Laboratory
RTLD	Rocket-Triggered Lightning Discharge
USAFA	United States Air Force Academy
V	Volt
XeCl	Xenon-chloride
μm	micro-meter (10^{-6} meters)

A Brief History of Laser Guided Lightning Discharge Models and Experiments

1. INTRODUCTION

Lightning and its possible capture for use has held the interest of scientists seemingly forever. Benjamin Franklin with his kite experiments attempted to understand the characteristics of lightning. Today, lightning discharge and possible capture have transcended Franklin's experiments to include several significant applications such as protection of space shuttle and missile launches, air traffic control, and energy capture and transmission, to name a few. These modern, possible applications are all related by research into lightning and, more specifically, artificially triggered lightning techniques.

This report will emphasize the history leading up to laser guided lightning discharges (LGLD), the research completed on laser induced lightning and the advantages and disadvantages of this particular triggered lightning technique.

2. BACKGROUND

Before LGLD are specifically addressed, lightning models and rocket-guided lightning discharges must be examined. Several studies have been conducted in an attempt to help identify the exact nature of lightning discharges. Since 1967 when Newman et al.¹ first succeeded in triggering lightning using the classical, rocket technique, other experiments have followed in the United States, Japan, France, Indonesia,¹ and China.²

Most notably, Mazur and Ruhnke³ report that they applied and evaluated Kasemir's theory [1950] of a bi-directional, uncharged leader. Mazur and Ruhnke also applied and evaluated the theory of a unidirectional, charged leader in an ambient electric field in order to help derive basic physical concepts applicable to processes of all lightning discharges, natural and triggered.³

They compared their theoretical predictions against rocket-triggered lightning discharges (RTLTD). They concluded that intracloud (IC) flashes closely resembled RTLTD in branching patterns, negative recoil streamer and positive leader channels and direction of negative pulses and recoil streamers.³ Mazur et al. also reported that "Waldteufel et al. [1980] determined that luminous images are produced by sequences of negative current pulses moving downward, and by ground potential waves (return strokes) moving upward (at $0.5-1.5 \cdot 10^8 \text{ ms}^{-1}$) along the branches on the positive leaders."³

Mazur and Ruhnke cited Kito et al. [1985], and Kawasaki and Mazur [1992] found, that rocket-triggered discharges under a positive space charge overhead were not followed by dart leaders or return strokes.³ Experiments conducted in Florida by Willett et al.,⁴ and jointly by the Centre Etudes Nucleaires de Grenoble (CENG) and the National Aeronautics and Space Administration (NASA), generated 202 of 299 RTLTDs for negative overhead space charge (67 percent success rate) and only 6 of 20 RTLTDs for positive overhead space charge (30 percent success rate). Liu et al. reported from similar results their RTLTD experiments in Gansu, China. Only 10 of 35 rocket launchers triggered discharges for positive overhead space charge (29 percent success rate).² This may be attributed to the greater amount of energy positive strokes carry. Therefore, positive strokes are more destructive when lightning is produced. Clearly, however, LGLDs will also face the problem of not being able to discharge clouds with positive overhead space charge easily.

3. THEORY

The theoretical models for cloud charge and flux density are given by Uman⁵ and Ruhnke and Kasemir [1988], respectively.²

$$B(t) = \frac{\mu I(t) H(t) [H^2(t) + D_B^2]^{-0.5}}{2 \pi D_B} \quad (1)$$

Where:

- B(t) = magnetic field
- μ = permeability of air
- I(t) = leader current
- H(t) = height of leader tip at any moment
- D_B = distance of magnetic flux density from base of triggered lightning

and

$$dE(t) = \frac{dQ(t) H(t) [H^2(t) + D_E^2]^{-1.5}}{2 \pi \epsilon} \quad (2)$$

Where:

- $dE(t)$ = change in field produced at distance D_E
- $dQ(t)$ = charge on the channel tip
- $H(t)$ = height of leader tip at any moment
- D_E = distance of electric flux density from base of triggered lightning
- ϵ = permittivity of air

These equations are the bases of characterizing RTLD. With reasonable certainty, we may also presume that the same characteristics and principles displayed by RTLD models should also be applied and exhibited by LGLD. This presumption, however, is a topic for further research as it has not been thoroughly studied.

Mazur and Ruhnke, from their study on bi-directional uncharged leaders and monopolar charged leaders, defined and outlined the main physical principles they found to govern lightning processes. The following nine points are taken directly from Mazur and Ruhnke.

"1. Lightning initiation in the atmosphere occurs as a bi-directional, uncharged leader and as an electrodeless discharge (IC [intra-cloud lightning], CG [cloud-to-ground lightning], aircraft-triggered, tipsy rocket-triggered flashes [non-grounded RTLD]), or at the ground as a monopolar, charged leader and as an electrode discharge (rocket-triggered flashes with grounded wire, lightning from tall buildings).

2. Induced charges on the leader are determined by the ambient potential distribution, with a net zero charge on the leader unless the leader is connected to the ground. In the latter case, and also in the return stroke process, a uniform charge per unit length is added to the channel, and the channel assumes the ground potential.

3. Any current-carrying leader channel is equipotential. This potential is determined by the environmental potential distribution. In the case of a leader triggered from the ground, and in the return stroke process, this potential is zero.

4. The electrical breakdown process at the leader tip depends only on the potential gradient there, which equals the difference between the leader potential and the cloud potential. This process drives leader development after initiation.

5. The growing branches of the leader act like current producers; current production continues only as long as branch propagation.

6. Branching of leaders creates a substantial "screening" of the electric fields in the parts of the channel at lower levels, and the propagation of lower branches ceases when the cloud potential at their tips is shadowed by the outer branches which are exposed to higher cloud potential. This results in a cutoff of current in lower parts of the leader channel. Branches that were choked remain conductive for a period of several milliseconds due to thermal ionization. New channels continue to be created as long as the breakdown process continues at the upper branches.

7. After current cutoff, the induced charges with opposite polarity to that at the leader tip increase on the bottom of the channel and on choked branches. This phenomenon is observed as the recovery of the E-field on the ground close to the flash. The opposite potential shifts in the upper, conductive, versus the lower, non-conductive channel, lead to a potential gradient sufficient for negative breakdown at the cutoff point. This produces recoil streamers in IC flashes, or dart leaders in CG flashes, and constitutes restoration of the bi-directional character of leader development.

8. The occurrence of recoil streamers on the negative end of the conductive channel is followed by increased positive charge on the opposite end, thus energizing the positive leader breakdown process there. A similar, but more powerful effect results from ground potential waves of return strokes following dart leaders. Thus a new cycle of interstroke processes (positive leader-cutoff-recoil streamer sequence) begins.

9. The leader channel ceases to propagate when the difference between the leader potential and the cloud potential at the tip is below the threshold levels required to continue breakdown. When that happens in all branches of the channel the entire lightning process comes to an end."³

Thus, under the assumption that triggered lightning discharges will behave like natural lightning discharges, theories and experiments have been proposed and conducted to determine the feasibility of LGLD using these principles.

4. EXPERIMENT

While comparatively much research and experimentation has been conducted on RTLD, little has been done to explore the laser option for guided lightning discharge. Some of the more notable attempts at LGLD were conducted in the USA and Japan. The Americans are primarily concerned with the problems lightning poses to aircraft and space vehicle launches, including the Space Shuttle, while the Japanese are more interested in the energy harvesting and power transmission line protection aspects of LGLD. See Appendix A for an economic analysis on potential use of lightning as a viable source of electricity.

LGLD have some inherent problems that must be overcome before a full-size, laser lightning guide can be implemented. In presenting LGLD, we must remember to separate the two entities composing artificial lightning -- triggering and guiding. On the laboratory scale, both Diels et al.⁶ and Shindo et al.¹ have been successful in triggering guided lightning discharges using lasers; however, due to the characteristics of the electromagnetic propagation through the air over large distances or times, several other factors must be addressed. Problems include:

1. The exact charge distribution function in clouds is not known.⁴ Some models suggest that the cloud charge density is evenly distributed.³ Others suggest that the charge can be assumed to be located at the center of the cloud.⁷ Still others assume that the charge is concentrated as a thin rod passing through the center of the cloud.⁷

2. The wavelength for optimization of lightning discharge and energy minimization is still undetermined. Shindo et al. experimented with a 10.6 μm pulsed CO_2 laser.¹ Diels et al. experimented with a 248 nm KrF femtosecond pulsed laser to trigger a discharge and a 530 nm

laser to maintain a conductive path⁶, while OPHIR Corporation⁸ proposed using a tunable dye laser with a Raman shifted 308 nm XeCl laser to produce a 314.5 nm laser to excite argon in the air.

3. Ionization of the surrounding air would cause the air to act as a conductor and hence absorb the laser's energy. This is known as inverse bremsstrahlung.¹ A conductive path is needed to direct the lightning discharge to ground, as lightning appears to follow the path of least resistance⁸, however, complete ionization of the air within a relatively short distance, as induced by high energy lasers at one of the resonant frequencies of air, would render LGLD ineffective. The resonant frequencies and ionization potentials for air's major components: nitrogen, oxygen, water, carbon dioxide, and argon must be addressed. A wavelength must be picked to minimize energy loss to ionization of the air while maximizing the range the laser beam propagates.⁹ Currently, laser-induced, ionized-air columns for triggered lightning guides have propagated at most some 60 meters before absorption of the laser beam¹; however, for the beam to discharge clouds, the beam must be capable of propagating on the order of 1000-3000 meters.

Shindo et al. propose that a series of focused laser beams, each creating a small ionized column, would eliminate the problem of electromagnetic absorption, but would still allow the lightning a preferred path for discharge.¹ Shindo et al. cite a discharge experiment using a 200 meter rope with pieces of metal strung out over several meters as the basis for their assumption.¹

4. Thunderstorms can either be positively or negatively charged. The negative overhead charged clouds were shown to be readily discharged; however, the positive overhead charge scenarios were either not dischargeable or had only a small occurrence of discharge.^{1,3,7} Whether both positively and negatively charged clouds can be discharged by the laser is yet to be determined.

5. When a cloud is triggered, the amount of time and energy it takes to discharge the entire cloud or cloud system may allow for recharging of the cloud. Recharging of the cloud system would still allow for triggering by another external source such as an airplane or spacecraft.

Both Diels et al.⁶ and Shindo et al.¹ were capable of LGLD on a laboratory scale; however, neither completed a full-scale experiment. Other experiments in LGLD are listed in Appendix B. Well known names in this field are listed in Appendix C.

5. DISCUSSION

Possible solutions to the problems facing LGLD include:

1. Producing a long plasma channel with a special focusing system in which the focusing surface is varied stepwise on a mirror (multi-focus system) or which has no definite focal length¹
2. Using a rapid but smooth motion of a focus toward the laser¹
3. Ionizing O₂ and/or N₂-- Diels et al. [1992], New Mexico⁶
4. Ionizing Argon -- OPHIR Corporation, NASA contract⁶

5. Using a pulsed microwave beam at a resonant frequency different from the major resonant frequencies of water, oxygen, carbon dioxide, argon, and nitrogen [Kozma, Wacker, & Gjone USAFA Physics 362 project, not published].⁹

Diels et al. cite the advantages of LGLD over RTLD including: 1) that the conductive volume created at the speed of light negates any space accumulated charge that can shield rocket guided discharges, 2) lasers will provide a ten-fold field enhancement, created by triggering the lightning at 1/10 of the self-breakdown field in air, while also providing a preferential discharge path that will prevent subsequent triggerings by other elements such as airplanes or rockets, and 3) laser triggering can be repeated at a rate exceeding 10 Hz while rockets cannot be continuously fired.⁵

Diels et al. report that "the discharge is guided by the light, as seen in the photograph [Figure 1.]. This result is significant, because the preferential path for the discharge is not along the beam. Indeed, in contrast to the experiment by the group in Japan, where the discharge is triggered between two needle shaped electrodes (hence there is a local field enhancement present prior to the creation of the laser induced plasma), our electrodes are profiled for uniform field. The holes leaving passage to the beam are profiled also. The field is minimum on axis, and the discharge should ultimately make contact at normal incidence with electrodes. The two extremities of the discharge are bent towards the normal to the profiled hole in the electrodes."⁶

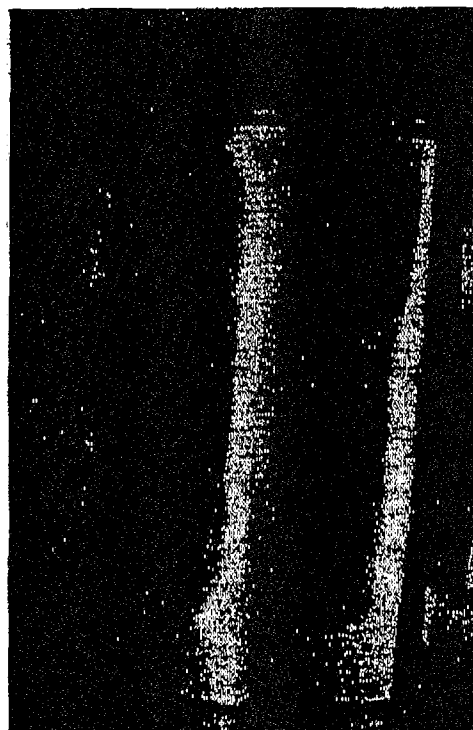


Figure 1. Electrical Discharge in the Laboratory Cell (1/7 atmosphere) Induced by a Nanosecond Pulse of the Excimer Laser (Peak Power 1 GW / cm²). The discharges follow the path of the beam, except that it bends towards a normal to the profiled electrodes at the two extremities.

[Taken directly from Diels et al.,⁶ Figure 15.]

6. CONCLUSIONS

Laser guided lightning discharges (LGLD) have dual-use potentials for aerospace safety, high-value asset protection, and electrical power applications, if technically refined. Proposed reliability and versatility characteristics of the laser exceed those of rocket-triggered lightning discharges (RTLTD). With LGLD, both the initial triggering and subsequent guiding of the induced lightning discharge must be accommodated. Although currently it is difficult to exactly predict the characteristics of thunderstorms and especially lightning, laser-triggered lightning discharges may help reduce some of the unpredictability of lightning. While it might be possible to use lightning as electricity, lightning harvesting as a viable energy source seems uneconomical at this time. Yet, theoretical models and experiments have been conducted examining and indicating the feasibility of the LGLD technique.

7. RECOMMENDATIONS

With LGLD successes on the laboratory scale, research and experimentation must shift to the actual building and testing of full-scale models. Research begun under Air Force and Phillips Laboratory contracts is now being undertaken by NASA contracts. LGLD dual-use potentials for aerospace safety, high-value asset protection, and electrical power protection and harvesting applications should continue to be tested and exploited for both military and civilian use.

References

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Appendix A

Feasibility Of Harvesting Lightning As An Electricity Source

The following set of calculations disprove the economic feasibility of harvesting electricity. Although the technology is readily becoming available to discharge a cloud and store its energy, it currently is not economically advantageous to do so. Some researchers have used the breakdown voltage of air (3 kV) to compute the possible value of harvesting lightning as electricity, but Dr. Stan Heckman's model incorporates experimentally determined, maximum cloud potentials and charge transfers in calculating the value of discharging a cloud. The values for cloud potential and the charge lightning transfers are taken from *The Lightning Discharge*, by Martin A. Uman.⁵

Cloud Potential	=	$10^8 - 10^9$	V
Charge Lightning Transfers	=	10	C
Total Energy _{Lightning}	=	$10^9 - 10^{10}$	J
Using the conversion factor:	1 kW·hr =	$3.6 \cdot 10^6$	J
<hr/>			
Total Energy _{Lightning}	=	300 - 3000	kW·hr

Value of electricity harvested by lightning, assuming that all of the charge within the cloud was withdrawn, at \$.06 kW·hr is \$20 - \$200. Using the full, air breakdown voltage of 3 kV would mislead one by a magnitude of three for a possible \$200,000 worth of electricity.

The above calculations were completed by Dr. Stan Heckman, Geophysics Scholar, Geophysics Directorate, Phillips Laboratory, Hanscom AFB, MA.

Appendix B

Related Papers, Reports, & Books On Lightning Modeling, Rocket-Triggered Lightning Discharge (RTL D), & Laser Guided Lightning Discharge (LGLD)

Author	Article Title	Journal Name	Yr	Vol	Pg
Aihara, Y.; T. Shindo; Miki; & T. Suzuki	Laser-guided discharge characteristics of long air gaps and observation of the discharge progressing feature	Transactions of the Institute of Electrical Engineers of Japan (Denki Gakkai Ronbunshi)	1992	112-B	668
Asinovskii, E.I.; L. M. Vasilyak; & S. Yu. Unkovskii	The space-time evolution of an electrical discharge directed by a laser spark	Soviet Physics-Technical Physics (Technical Physics)	1992	62	183
Barnes, A. A.	Predicting Triggered Lightning	International Conference on Lightning and Static Electricity	1989	9.B.1	
Dwyer, T.J.; J. R. Greig; D.P. Murphy; J. M. Perin; R. E. Pechacek; & M. Raleigh	On the Feasibility of Using Atmospheric Discharge Plasma as an RF Antenna	IEEE Transactions on Antennas and Propagation	1984	32	141
Eriksen, Fredrick J.; Terence H. Rudolph; & Rodney A. Perala	The Effects Of The Exhaust Plume On The Lightning Triggering Conditions For Launch Vehicles	NASA International Aerospace & Ground Conference on Lightning and Static Electricity, Pub. 3106	1991	1	65-1
Fetzer, G. J.	Another Look at the OPHIR Laser Lightning Rod	OPHIR Corporation, Lakewood, CO	1989		
Fetzer, G. J.; J. E. Stockley; & L. J. Radziemski	Perturbation of the local charge concentrations in the atmosphere due to high irradiance laser beams	Proceedings of SPIE Symposium on Innovative Science and Technology for Government and Civilian Applications, O/E Laser Conference, Los Angeles, CA	1989		

Author	Article Title	Journal Name	Yr	Vol	Pg
Fetzer, G. J.; J. J. Rocca; & G. J. Collins	Model of a CW argon ion laser excited by low electron beams	Journal of Applied Physics	1986	60	2739
Grieg, J. R.; D. W. Koopman; R. F. Fernsler; R. E. Pechacek; I. M. Vitkovitsky; & A. W. Ali	Electrical discharges guided by pulsed CO ₂ -laser radiation	Phys. Rev. Lett.	1978	41	174
Iris, M.; T. Shinkai; K. Araki; & S. Yoshikawa	Temporal decay of an atmospheric plasma leader stroke for lightning initiation	Univ. College Swansea, Swansea UK, Conf.	1992	2	576
Klingbeil, Ralph; & Derek A. Tidman	Theory and Computer Model of the Lightning Stepped Leader	Journal of Geophysical Research	1974	79	865
Koopman, David W.; & K. A. Saum	Formation and guiding of high-velocity electrical streamers by laser-induced ionization	Journal of Applied Physics	1973	44	5328
Kubo, M.; R. Itanani; & S. Matsumura	Basic research for laser triggered lightning-influence of wavelength of laser on atmospheric spark discharge	Transactions of the Institute of Electrical Engineers of Japan (Denki Gakkai Ronbunshi)	1992	112-A	620
Kumar, V.; & R. K. Thareja	Laser-induced gas breakdown in the presence of a static electric field	Journal of Applied Physics	1988	64	5269
Lencioni, D. E.	Laser-induced air breakdown for 1.06 μ m radiation	Appl. Phys. Lett.	1974	25	15
Lippert, J. R.	Laser-induced lightning concept experiment	Air Force Flight Dynamics Laboratory AFFDL-TR-78-191	1978		
Miki, M.; Y. Aihara; & T. Shindo	Development of long gap discharges guided by a pulsed CO ₂ laser	Journal of Physics D (Applied Physics)	1993	26	1244
Miki, M.; Y. Aihara; & T. Shindo	Model experiments of laser- triggered lightning	Dresden Univ. Technology, Germany, Conf.	1991	8	39

Author	Article Title	Journal Name	Yr	Vol	Pg
Nakamura, K.; T. Suzuki; C. Yamabe; & K. Horii	Fundamental research for laser-triggered lightning- laser-triggered spark gap without the irradiation of the surface of electrodes using UV lasers	Univ. College Swansea, Swansea UK, Conf.	1992	2	588
Nakamura, Koichi; Atsushi Wada; & Kenji Horii	Discussions On A Long Gap Discharge To An EHV Transmission Tower By A Rocket Triggered Lightning Experiment	NASA International Aerospace & Ground Conference on Lightning and Static Electricity, Pub. 3106	1991	1	62-1
Nelson, Loren D.	A Laser Lightning Triggering System for Forecasting and Mitigating Lightning Hazards	OPHIR Corporation, Lakewood, CO -- NASA Proposal # SBIR 89- 1-II-13.03-1512	1990		
Raizer, Y. P.	Laser Induced Gas Discharge Phenomena	Consultants Bureau, New York, NY	1977		
Sasaki, J.; S. Kubodera; R. Ozaki; & T. Uchiyama	Characteristics of interelectrode flashover in air with the existence of a weakly ionized plasma channel induced by a KrF laser (248nm)	Journal of Applied Physics	1986	60	3845
Sato, K.; Y. Achiba; & K. Kimura	A photoelectron spectroscopic study of ionization selectivity in resonantly enhanced multiphoton ionization of Xe and Kr	Journal of Chemistry and Physics	1984	80	57
Schubert, C. W., Jr.	The laser lightning rod system: A feasibility study	Air Force Flight Dynamics Laboratory AFFDL-TR-78-60	1979		
Taylor, A. J.; T.R. Gosnell; J. P. Roberts; D.C. MacPherson; & C.R. Tallman	Characterization of a high- intensity sub-picosecond XeCl laser system	Los Alamos National Lab, NM Report # LA-UR-90-1692 CONF-9005210-2	1990		
Uman, M. A	The Lightning Discharge	Academic Press	1987		
Uman, M. A.	Lightning	Dover Publications Inc., New York, NY	1984		
Willett, John C.	Rocket-Triggered-Lightning Experiments In Florida	Res. Lett. Atmos. Electr.	1992	12	37

Author	Article Title	Journal Name	Yr	Vol	Pg
Yamabe, C.; K. Nakamura; & K. Horii	Technology for triggered lightning by using laser beam	Oyo Buturi	1992	61	718

Appendix C

Names In The Field

Aihara, Yoshinori	Institute of Electrical Engineers of Japan
Barnes, Arnold A.	Geophysics Directorate, Phillips Laboratory, Hanscom AFB, MA
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Heckman, Stan	Geophysics Scholar, Geophysics Directorate, Phillips Laboratory, Hanscom AFB, MA
Kasemir, H. W.	New Mexico Institute of Mining, Socorro, NM
Kawasaki, Zen	Osaka University, Osaka, Japan
Liu, Xinsheng	Lanzhou Institute of Plateau Atmospheric Physics, Chinese Academy of Sciences, China
Miki, Megumu	Central Research Institute of Electric Power Industry, Tokyo, Japan
Mazur, V.	National Severe Storms Laboratory, Norman, OK
Nelson, Loren D.	OPHIR Corporation, Lakewood, CO
Ruhnke, Lothar H.	Reston, VA
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